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## DIAMOND CHEMICAL VAPOR DEPOSITION

Diamond possesses numerous physical and chemical properties that have technological, industrial, and scientific applications. It has the highest thermal conductivity and hardness of any material, high optical transmission, a large bandgap and high carrier mobilities, and the lowest friction coefficient (under select conditions) [1,2]. These properties make diamond of particular interest to the electronics community for use as a heat spreader for thermal management or as an active electronics device material [3].

The current interest in diamond surface chemistry reflects recent advances in diamond growth by chemical vapor deposition (CVD), under what were once thought to be thermodynamically impossible conditions. Figure 1 is a schematic diagram of the CVD process [4]. CVD deposits diamond from a gas-phase mixture of hydrogen ($H_2$), hydrocarbon (usually methane, $CH_4$),and sometimes an oxygen-containing species or halogen ($O_2$, CO, $Cl_2$, HCl). The gases in the growth chamber are activated by various methods including microwave or radio frequency plasmas, DC discharge, combustion flame, or even a hot metal filament. All of these techniques fragment the hydrocarbon molecules to form a "soup" of hot hydrocarbon molecules and fragments. Most importantly, they split the hydrogen molecules into atomic hydrogen. The resulting hydrocarbon

and atomic hydrogen species move through the reactor by diffusion and convection and impinge on the substrate. Adsorption, diffusion, reaction, and desorption of various species occur simultaneously on the substrate surface. Under a select set of conditions, diamond nucleates and
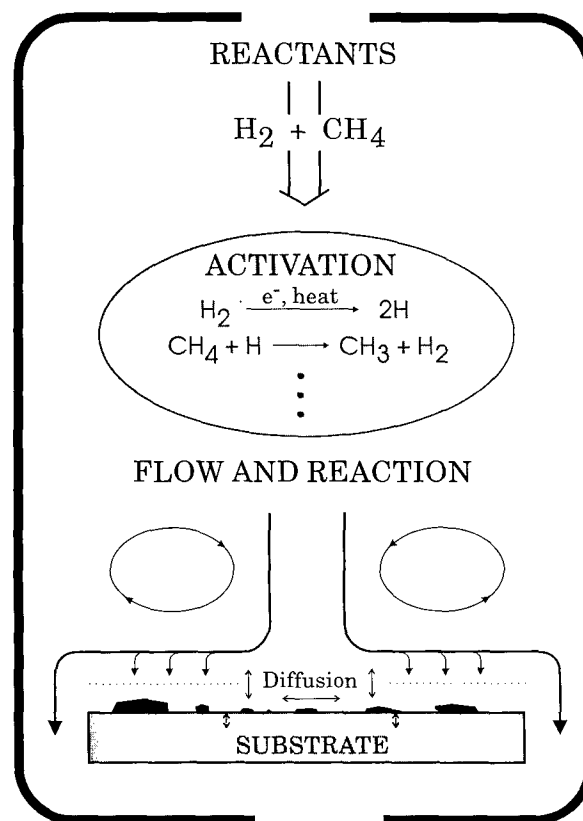


Fig. 1 — Schematic rendition of the CVD diamond deposition process. (Originally published in Ref. 4)

grows while the deposition of graphitic (or $sp^2$) carbon formation is suppressed.

Hydrogen and oxygen play multiple roles in CVD diamond growth, both in the gas phase and on the surface of the growing film [5]. The principal effects of atomic hydrogen on the diamond growth process are thought to include: control of the gas phase chemistry, stabilization of the $sp^3$-hybridized surface carbon atoms, preferential reaction with $sp^2$-hybridized carbon, and abstraction of adsorbed hydrogen to produce reactive surface sites for carbon incorporation. Gas-phase hydrogen atoms (H) can adsorb on the surface and fill vacant sites or abstract surface hydrogen to form volatile molecular hydrogen. The desorbing hydrogen creates vacant surface sites and radicals at which methyl radicals and other hydrocarbon species adsorb and which are ultimately incorporated into the growing diamond lattice. The competing adsorption, desorption, and abstraction processes create a dynamic balance that leaves some open surface sites for addition while not completely denuding the surface of adsorbates. Such denuded (unterminated) surfaces rapidly develop double bonds and nucleate undesirable $sp^2$-bonded carbon. Adsorbed hydrogen stabilizes the diamond surface and explains why diamond grows under CVD conditions. Oxygen species likewise bond at vacant surface sites and create open sites by desorbing or abstracting other surface species. At elevated temperatures, oxygen etches both $sp^2$ carbon (graphite) and $sp^3$ carbon (diamond) surfaces.

The complex CVD process is controlled by the thermodynamics and kinetics of multiple competing deposition and etching surface reactions. Our objective is to understand and improve the CVD process by studying the structure and thermal stability of the bare diamond surface and surfaces terminated with hydrogen, oxygen, or hydrocarbons. We also must understand heat-induced desorption products and the interaction between gas phase species and diamond surfaces terminated with other species. This knowledge is essential for developing the diamond growth models and process controls required to optimize growth rates, morphology, quality, and the post-deposition surface manipulation necessary to exploit diamond's superb materials properties.

## THE DIAMOND SURFACE

The diamond surfaces studied at NRL include both single crystals and polycrystalline films. The single crystals are either natural stones, man-made in a high-temperature/high-pressure (HTHP) press, or CVD-grown homoepitaxial layers on natural or HTHP stones. The homoepitaxial layers are especially useful since many natural and HPHT diamonds are insulating and hence unsuitable for many electron-based analyses because of surface charging. Small amounts of boron or other dopants introduced into the feedgas make the CVD-grown layers electrically semiconducting.

Diamond surface chemistry presents unique challenges and pitfalls. Surface chemistry in general, and CVD growth in particular, can occur principally at steps, ledges, and other defects. Crystals cut off-axis have higher densities of defect and ledge structures, which can lead to variable or unrepresentative data for surface reactions on a particular crystallographic surface. Commercially available diamonds are only cut to within 2° of the low-index ((100), (110), and (111)) faces, limiting their utility for some studies. Useful experiments require knowledge of how closely the sample surface matches the low-index planes and how smooth those surfaces are, along with confirmation that the surface remains essentially unchanged and uncontaminated by $sp^2$ carbon or other species during various treatments. The diamond grit polishing often used to finish diamond surfaces hinders formation of scientifically useful diamond surfaces by creating large numbers of microscopically rough surface wear tracks and pits. Sputtering and vacuum annealing techniques used in the surface science of metal crystals cannot be used because they convert the diamond surface to graphite. However, recent scanning tunnelling microscope (STM) work [6] and our own low-energy electron diffraction (LEED) and STM results show that (100) and (110) diamond surfaces heated to 800°C in a microwave hydrogen plasma become

reproducibly smoother and well-ordered, with dramatically lower step and other defect densities. Such representative surfaces are proving highly useful for surface science and homoepitaxial growth studies.

## SURFACE ANALYSIS

Most of our experiments are conducted in ultrahigh vacuum (UHV) chambers with base pressures of 1-5 $\times$ 10$^{-10}$ Torr (Fig. 2). Independent heating and cooling capabilities allow control of the diamond surface temperature. Diamond surfaces at various temperatures are dosed with molecular hydrogen (H$_2$), deuterium (D$_2$, an isotope of hydrogen), or oxygen (O$_2$) by backfilling the chamber. During some experiments, a tungsten filament heated to > 1800°C excites H$_2$ or D$_2$ and dissociates a fraction of it to highly reactive atomic hydrogen (H) or deuterium (D). A hot (1150°C) iridium (Ir) filament excites molecular oxygen to more reactive vibrational and electronic states, and may convert some fraction to highly reactive atomic oxygen (O). The flux of atomic species to the diamond surface is unknown, so the doses listed are the total flux of the molecular species in Langmuirs (1 L = 10$^{-6}$ Torr s).

We use a variety of electron-based, optical, and mass spectrometric techniques to interrogate the interactions between gas-phase species and diamond surfaces. Vibrational spectroscopies provide chemical bond information about adsorbates and surface structure. In high-resolution electron energy loss spectroscopy (HREELS), monochromatic low-energy electrons are scattered from the surface of interest and lose measurable amounts of energy through excitation of surface adsorbate and lattice vibrations. The specific amount of energy lost to these vibrations identifies the surface chemical species; the number of electrons losing that amount of energy reveals the surface coverage of that species. We obtain similar information with IR photons by multiple internal-reflection infrared spectroscopy (MIRIRS).

Auger electron and X-ray photoelectron spectroscopies (AES and XPS) provide compositional and chemical identification of the diamond surface (i.e., whether it is sp$^2$ or sp$^3$



Fig. 2 — A view into the UHV chamber used for HREELS and other analysis of diamond surfaces. The small square in the center of the shot is a piece of polycrystalline diamond film. The light comes from a heater in back of the sample. (Photo courtesy J. McNally)

bonded carbon and whether it is contaminated with other species), and give the type and extent of non-hydrogen surface termination. Secondary electron emission (SEE) and electron loss spectroscopy (ELS) also confirm whether the surface is diamond or contains sp$^2$ carbon contamination. LEED measures the degree of surface order. Low-energy electrons scattered from a surface that consists of a regular array of atoms undergo constructive and destructive interference, which are observed as spots on a phosphor screen. The spot patterns are characteristic of the surface structure. The sharpness and contrast of the spots increase with respect to the background as the surface order improves. A differentially pumped, random flux-shielded, quadrupole mass spectrometer measures desorption products vs surface temperature in temperature programmed desorption (TPD) experiments. The adsorbate surface coverage after various treatments is obtained by integrating the area under the desorption curve. The combination of chemical species-specific probes

(HREELS, AES, XPS, TPD) and techniques sensitive to surface structure (LEED, STM) provides a detailed picture of the diamond surface and adsorbates.

## HYDROGEN CHEMISTRY ON DIAMOND SURFACES

The stretch and bend vibrational frequencies observed with HREELS reveal the C-H and C-C bonding on hydrogenated diamond surfaces. The C-H stretching frequency at 2800-3000 cm$^{-1}$ increases in the order $CH_3 < CH_2 < CH$, and also increases for hydrogen bonded to single, double, and triple-bonded carbons. HREELS shows that molecular hydrogen does not react with nude, room-temperature, polycrystalline diamond surfaces composed primarily of (111) facets. However, *atomic* hydrogen adsorbs on the surface in the monohydride state (CH, not $CH_2$ or $CH_3$) with C-H bonds normal to the surface and the surface carbon in the sp$^3$, single-bonded configuration. Upon heating the diamond to $T > 900°C$, the H desorbs from the surface, as evidenced by the disappearance of the C-H vibrational stretch and bend features. TPD shows that the hydrogen desorbs exclusively as $H_2$. Hydrogen abstraction rates are determined by using HREELS to monitor the disappearance (appearance) of the C-H (C-D) stretch after successive doses with excited deuterium (D), a hydrogen isotope with a different stretching frequency (Fig. 3). These results indicate that hydrogen adsorption on a diamond surface at 80°C occurs 20 times more efficiently than abstraction, higher than in analogous gas phase reactions. Current attempts to model CVD diamond surface reactions use numbers derived from gas phase reactions, and thus can be improved. The adsorption and abstraction rates are unchanged on diamond at 600°C. The independence of the rates on surface temperature indicates that the incident hydrogen atoms are not in thermal equilibrium with the surface during these reactions. Consequently, the reaction mechanism for hydrogen abstraction is best described as the direct collision of an H atom with a diamond site, which results in either adsorption or removal of a surface hydrogen.
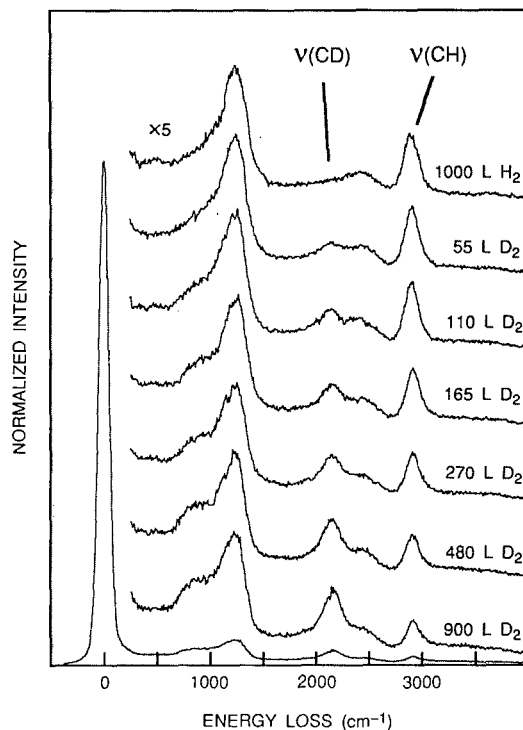


Fig. 3 — A series of HREELS spectra showing the gradual replacement of the C-H stretch and bend modes by those of C-D as the sample is dosed with excited deuterium

Diamond (100) surfaces can also be denuded by annealing in vacuum or reterminated by dosing with hydrogen or oxygen. Surfaces stripped of surface-terminating groups sometimes eliminate the energetically unfavorable "dangling bonds" by rearranging the surface atoms to form new bond configurations, often accompanied by changes in the bond angles and atom positions near the surface. There are several proposed configurations for the hydrogen-saturated C(100) surface. Figure 4 is a schematic rendition of possible structures for hydrogenated (100) diamond. Our HREELS and LEED data indicate that hydrogenated C(100) has a monohydride dimer structure with every surface carbon atom bonded to one hydrogen atom and three other C atoms. The (100) diamond surface exposed to hydrogen atoms exhibits a two-domain, 2 × 1 LEED pattern (Fig. 5(a)), which is consistent with this structure. A surface with dihydride carbon atoms has a square 1 × 1 LEED pattern. In addition,

(a) dihydride

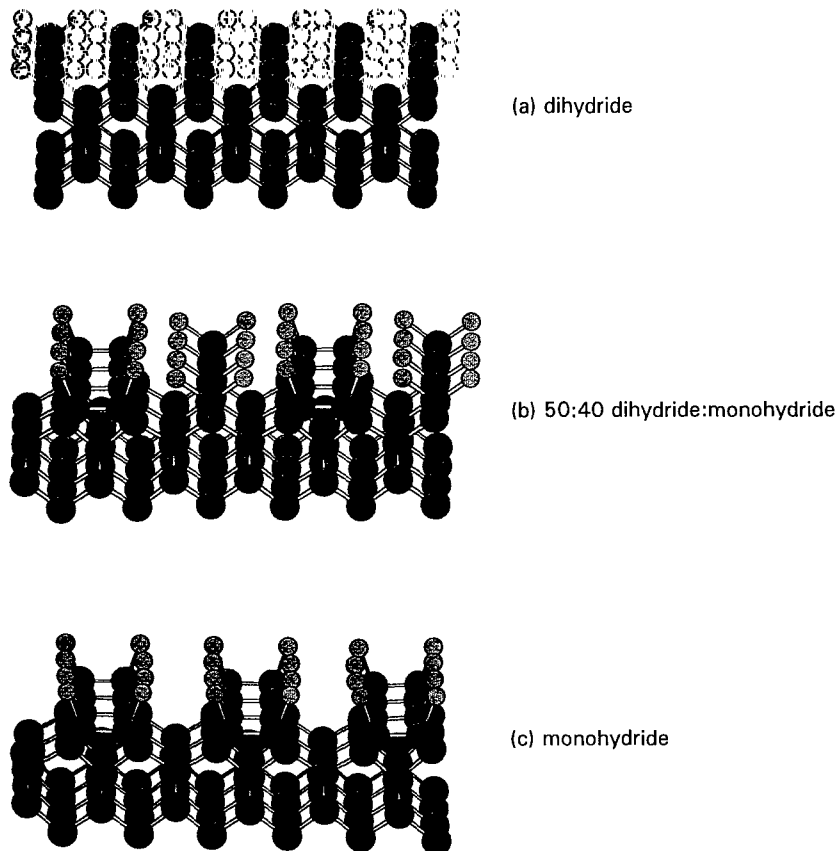(b) 50:40 dihydride:monohydride

(c) monohydride

Fig. 4 — Three possible structures for the hydrogenated diamond (100) surface; (b) and (c) relax the severe steric constraints of (a). (Originally published in Ref. 5)



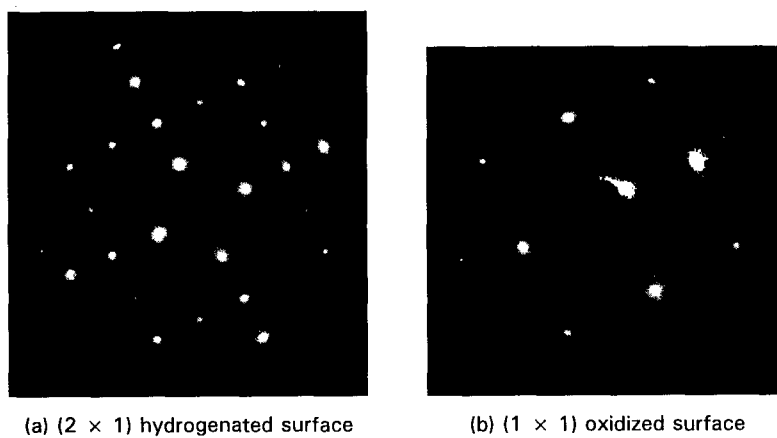(a) (2 × 1) hydrogenated surface     (b) (1 × 1) oxidized surface

Fig. 5 — Low-energy electron diffraction (LEED) patterns on (100) diamond

the HREELS stretching vibrational frequency indicates that there are CH groups on the surface, but no $CH_2$ groups. The $2 \times 1$ LEED pattern persists even after the sample is heated to almost 1100°C, but the accompanying loss of the HREELS C-H stretching vibration confirms the desorption of most of the surface hydrogen. The appearance of several new vibrational peaks suggests changes in the surface carbon-carbon bonding, consistent with a pi-bonded dimer reconstruction at adjacent open sites. ELS, SEE, and AES all confirm the partial conversion of the surface to $sp^2$ carbon under these conditions. This reconstruction is not desirable during CVD because it is the first step toward graphite growth, which degrades the quality of the deposited diamond.

The LEED patterns from hydrogenated (110) faces also sharpen and brighten in a hydrogen plasma, indicating a smoother, more well-ordered surface. The background $H_2$ partial pressure impedes TPD measurement of hydrogen desorption from the diamond surface. For these studies, diamonds are exposed to D atoms created with the hot tungsten filament. TPD shows that neither molecular hydrogen nor deuterium react with bare diamond (110) surfaces at room temperature, but that atomic hydrogen and deuterium do chemisorb. Conversely, a deuterated surface heated to 1027°C evolves molecular deuterium $(D_2)$. We expect adsorption and desorption to be reversible processes. Therefore the adsorption of H(D) atoms and the desorption of $H_2$ $(D_2)$ molecules indicates that molecular hydrogen requires additional energy (i.e., there is an activation barrier) to react with the bare surfaces.

Figure 6 shows $D_2$ thermal desorption spectra from a C(110) surface that was exposed to $D_2/D$ at room temperature. The surface coverage derived from the desorption spectra saturates at exposures of ~200 L. Molecular deuterium desorbs between 227°C and 1027°C, yielding an asymmetric desorption peak with a coverage-independent maximum at 892°C. The peak shape and invariant maximum temperature are characteristic of desorption kinetics which are first order in (directly proportional to) the adsorbate atomic D concentration. Recombinative desorption rates usually depend on the
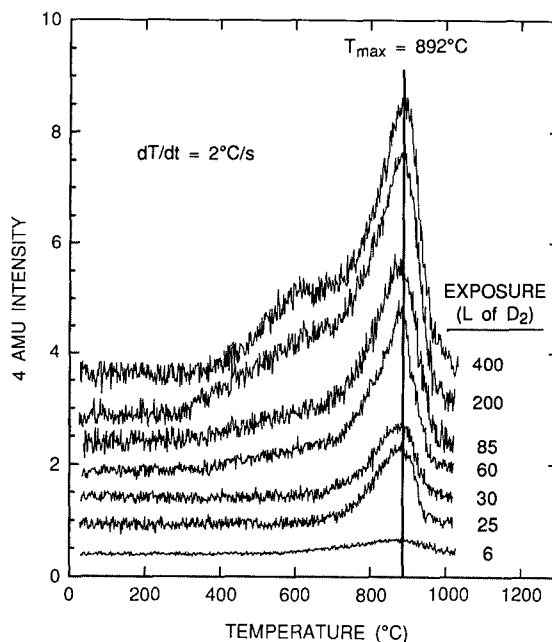


Fig. 6 — Temperature-programmed desorption spectra from a hydrogenated diamond (110) surface exposed to excited deuterium at 27°C

probability of collision between two adsorbate atoms, which is proportional to the square of the surface species concentration. The apparent first-order recombinative desorption kinetics for $D_2$ desorption implies that the rate-limiting step for the overall kinetics is not molecular desorption, but another step in the sequence of events preceding desorption. The actual rate-limiting step could be generation of a reactive site, the mobility of surface species, or another event directly proportional to surface hydrogen concentration.

## OXYGEN CHEMISTRY ON DIAMOND SURFACES

Oxygen also adsorbs on the diamond surface, terminating surface sites and influencing the surface rearrangement and availability of sites for hydrocarbon addition. The dominant C-O surface species varies with the specific diamond face and reaction temperature. TPD shows that oxygen desorbs from the diamond surface as either CO or $CO_2$, so the desorbing oxygen removes carbon atoms and etches the diamond surface. Desorption of different O-containing surface groups requires cleavage of

different numbers of C-O bonds, which influences the oxygen desorption temperature and the relative oxidative stability of each face. Polycrystalline diamond films composed primarily of (111) facets and dosed with atomic oxygen develop a HREELS feature at 1000-1080 cm$^{-1}$. This is consistent with oxygen in an ether (bridge-bonding) configuration spanning two surface carbon atoms. The HREELS feature corresponding to ether-bonded oxygen disappears after an oxidized (111) sample is heated in vacuum to desorb the surface oxygen. Most of the oxygen desorbs at lower temperatures ($T < 750°C$) than hydrogen ($T > 950°C$) and so lowers the temperature needed to form vacant surface sites for the addition of hydrocarbon species to the diamond lattice. Oxygen also reacts with surface hydrogen and removes it from the diamond surface at 450°C.

Exposure of the hydrogenated (100) diamond surface to excited oxygen converts the LEED pattern from a sharp 2-domain $2 \times 1$ to a $1 \times 1$ pattern (Fig. 5(b)). This is consistent with cleavage of the carbon dimer bonds present on the hydrogenated surface. HREELS spectra from oxidized (100) surfaces have a feature at 1720 to 1800 cm$^{-1}$, corresponding to oxygen atoms double-bonded to single carbon atoms (a carbonyl or ketone).

Neither UHV annealing to desorb surface hydrogen nor oxidation with excited oxygen alters the LEED pattern on (110) diamond, so that surface probably does not reconstruct. The HREELS spectra show both carbonyl and ether-bonded oxygen. TPD and AES reveal that the bare (110) diamond surface at 0°C becomes oxygen-saturated when exposed to 600 to 1200 L of oxygen excited with an Ir filament. The broad CO and $CO_2$ TPD desorption features from the oxidized surface have maximum desorption rates at $\sim$ 597°C and 527°C, respectively. The CO desorption intensity is an order of magnitude higher than for $CO_2$, indicating that most of the oxygen leaves the surface as CO. The CO and $CO_2$ desorption peak maxima and temperature range are independent of the oxygen surface coverage, suggesting that CO and $CO_2$ desorption also follow first-order kinetics. The desorption activation energy for the majority of CO and $CO_2$ species on the

surface is estimated at 55 and 51 kcal/mole, respectively. If the oxygen-covered surface is annealed to desorb part of the oxygen monolayer, cooled, and then reheated to 1027°C, the final CO thermal desorption curve continues where the preheated desorption curve ends. This indicates that oxygen adsorbs in a distribution of sites on the surface and that the sites are inaccessible to each other by diffusion of the surface oxygen.

## POST-DEPOSITION APPLICATIONS OF DIAMOND SURFACE CHEMISTRY

### Implantation and Electrochemical Etch

Diamonds are usually cleaned with boiling acids or an oxygen plasma to remove non-diamond carbon and metal contaminants prior to use in device fabrication. Both treatments oxidize diamond to similar levels and alter its electrical characteristics. High-temperature annealing and/or hydrogen plasmas eliminate the surface oxygen and restore surface conductivity and other electrical characteristics. Thus, surface termination and reconstruction are critical to the characteristics and reproducibility of diamond-based devices.

Under some conditions, the diamond surface oxidizes to even higher levels than observed with acids or oxygen plasmas. The surface of a diamond immersed in a distilled water bath between two electrodes with a 50 to 300 V potential applied between them oxidizes to a higher degree than in plasma or acid baths alone, although the diamond itself does not appear to etch. However, regions of the diamond damaged by ion implantation not only oxidize but are electrochemically etched. High-energy ion implantation creates subsurface damage in the region of the crystal lattice where the ions come to rest, leaving a relatively undamaged outer layer. Selective removal of the subcutaneous damage layer with the electrochemical etch undercuts the relatively undamaged top layer to produce a very thin sheet of high-quality diamond [7]. Figure 7 shows a 50-nm-thick diamond sheet curling up from an implanted and partially etched polycrystalline diamond film.

Fig. 7 — Scanning electron micrograph of a thin (50-nm) sheet of diamond lifting off of a polycrystalline film implanted with 170 eV carbon ions and partially electrochemically etched in distilled water. Magnification is 100×.

The relatively undamaged top surface of implanted crystals provides a template for further diamond growth. Implanted single crystals subjected to CVD growth prior to electrochemical etching develop a homoepitaxial diamond layer on the top surface, i.e., the lattice of the CVD-diamond layer is a continuation of the crystal lattice of the substrate. The high quality of the diamond film is confirmed by Raman spectroscopy, the flat growth surface, and regular 90° crystalline fractures on stressed films. CVD growths thicken and stiffen the liftoff layer so that it does not curl. The resulting "tiles" can be placed on a surface and arranged into a mosaic. Further CVD growth on the diamond tiles could create a sheet of virtually "single-crystal" diamond over large areas and irregular surfaces. We have produced a metal-insulator-semiconductor (MIS) capacitor from homoepitaxial diamond grown on the liftoff layer and then coated with $SiO_2$ and appropriate metal patterns. An array of such devices would constitute a charge-coupled device (CCD) and could function as an uncooled, back-illuminated UV imager that is insensitive to visible light.

## Surface Functionalization and Electroless Metallization

The diamond surface can be chemically manipulated to facilitate metallization and attachment of other technologically useful thin films for microelectronic device fabrication, sensors, etc. Attaching adherent metal coatings to diamond by using traditional evaporation or sputtering approaches usually requires pre-sputtering of the diamond surface before metallization, or annealing to 900°C to form an intermediate carbide layer. Both techniques are problematic for many applications and can have a deleterious effect on desired interfacial electrical characteristics because of surface graphitization or dopant diffusion. These problems are eliminated with a new NRL process in which a metal-binding self-assembled (SA) organosilane film chemisorbs onto a diamond surface previously oxidized by one of the techniques discussed earlier [8]. The SA films can be patterned by either direct exposure to UV radiation or by photoresist masking techniques. Immersion of the patterned SA film surface into an aqueous palladium catalyst solution results in selective attachment of the catalyst to the patterned SA film. When the substrate is then placed in an electroless plating bath, metal selectively deposits in an additive fashion onto the catalyzed region of the surface (Fig. 8). The resulting patterned metal films adhere to the diamond without sputtering or annealing.

## SUMMARY

Diamond has great potential in a diverse array of technological applications. These include passive and active electronics, as well as numerous other tribological, optical, and coatings applications. However, the current knowledge of diamond surface chemistry is inadequate for full exploitation of this potential. We are pursuing increased understanding of diamond surface chemistry to improve the CVD process and post-deposition manipulation of the surface chemistry for metallization and other applications. We obtain such chemical knowledge by preparing representative diamond surfaces and monitoring their interactions with a variety of
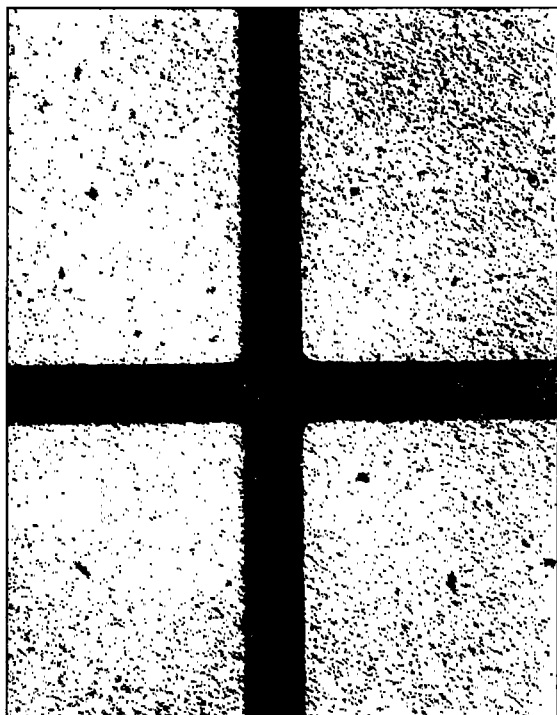
Fig. 8 — Optical micrograph of a polycrystalline diamond film after functionalization, patterning and metallization with 100 nm of Ni. The Ni-coated regions are light colored; the unmetallized diamond film is dark. Magnification is 50×.

gases under different pressure and temperature conditions, and by developing and implementing new processes for diamond surface modification. The resulting chemical insight aids in the development of superior diamond growth processes and surface manipulation techniques of use to the Navy, as well as the industrial and scientific communities.

## ACKNOWLEDGMENTS

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## THE AUTHORS

**Pehr E. Pehrsson** received a B.S. degree in chemistry from the College of William and Mary in 1978, and a Ph.D. in physical chemistry from the Catholic University of America in 1985. His dissertation topics included ion implantation of polymers and Auger lineshape analysis of transition metal carbides. He was an NRC/NRL Postdoctoral Fellow in the Electronics Science and Technology Division of the Naval Research Laboratory from 1985-1987, where he investigated laser-induced chemical vapor deposition and surface modification of SiC. Dr. Pehrsson joined the Chemistry Division at NRL in 1987; his work involves the surface science of high-temperature chemistry, including carbon oxidation and the nucleation and growth of diamond by chemical vapor deposition. In addition, he is active in functionalization of diamond surfaces and selective chemical vapor deposition of metals.

**John N. Russell, Jr.** received degrees in chemistry from Dickinson College (B.S. degree, 1981) and The University of Pittsburgh, (Ph.D., 1987). His dissertation topics included the surface chemistry of organic molecules on single-crystal metal surfaces and the adsorption/desorption kinetics of hydrogen on nickel. He was a Postdoctoral Fellow at the Corporate Research Science Laboratories of the Exxon Research and Engineering Company from 1987 to 1989. At Exxon, his research encompassed laser-induced-desorption studies of surface diffusion and time-resolved nonlinear spectroscopy measurements of surface reaction kinetics. Dr. Russell joined NRL in 1989; his research involves studies of diamond surface structure and chemistry, and the fundamental mechanisms of chemical vapor deposition processes. Dr. Russell is a member of the American Chemical Society, the American Physical Society, and the American Vacuum Society.

**Brian D. Thoms** received degrees in physics from the University of Illinois at Urbana-Champaign (B.S., 1983) and Cornell University (M.S., 1986, Ph.D., 1991). His thesis research involved studies of the interactions of hydrogen and hydrocarbons with silicon surfaces. Dr. Thoms has been at NRL as a National Research Council postdoctoral research associate since 1991. At NRL, he has used electron-based spectroscopic techniques to investigate the influence of hydrogen atoms on the structure and bonding of diamond surfaces. Specific problems he has addressed include the measurement of adsorption and abstraction rates on polycrystalline diamond surfaces, the structure of bare and hydrogen-terminated C(100), and the scattering mechanism of low-energy electrons from diamond surfaces.

**James E. Butler** received a B.S. degree in chemical physics from the Massachusetts Institute of Technology in 1966, and a Ph.D. in chemical physics from the University of Chicago in 1972. He was a postdoctoral fellow at the National Institutes of Health from 1972 to 1974, and a research fellow at the James Franck Institute at the University of Chicago from 1974 to 1975. Dr. Butler joined NRL in 1975, where he is currently the head of the Gas/Surface Dynamics section of the Chemistry Division. In that capacity he has coordinated and managed NRL's diamond CVD program. His current interests include chemical processes occurring in the growth and etching of solid-gas interfaces, spectroscopy and structure of transient surface and gaseous species, excited states of molecules, and collision and reaction kinetic processes in gas phase and on surfaces important to various chemical vapor deposition processes. He is a member of the American Physical Society, Optical Society of America, Coblentz Society, Sigma Xi, Chemical Society of Japan, and Materials Research Society.

**Michael Marchywka** earned the BSEE degree from the University of Michigan in May, 1984 and the MSEE degree in 1985. He worked on instrumentation for magnetic recording research at Kodak Research Laboratories before coming to NRL in 1988. At NRL, he has worked on various phases of UV and vacuum UV detection and instrumentation. This work has included the measurement of silicon detector properties, design of laboratory test equipment, and development of processing techniques for fabricating UV detectors based on semiconducting diamond. Three patent applications have resulted from his recent work. Mr. Marchywka is a member of Tau Beta Pi, the national engineering honor fraternity.

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